

## **Hydrodynamics and Roughness of Irregular Boundaries**

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### **LONG-TERM GOALS**

The research goals of the ongoing work target accurate parameterization and modeling of nearshore waves, currents and turbulence in complex reef environments. A central theme of this work is the response of steady and oscillating flow to highly irregular, broad-banded roughness. Previous ONR supported study by the PI's group have quantified reef roughness, examined the hydrodynamic response to a variable roughness at small scales and explored the relationship between hydrodynamic and physical roughness.

### **OBJECTIVES**

Specific goals for the work include developing methods for quantifying physical roughness scales in reef environments using an autonomous underwater vehicle (AUV) and determining the hydrodynamically relevant roughness scales for wave and current flow.

The work underway is also enabling development of a series of practical applications including examination of the relationship between measured roughness and sidescan imagery, exploration of AUV-based ADCP observations for resolution of steady flow boundary layer dynamics, and implementation of new tools for measurement of turbulent stresses in wavy environments. In addition high-resolution reef morphology data will enable further study on the correlation between roughness and other measurable reef characteristics including coral color, health and species.

### **APPROACH**

To achieve the objectives detailed above, we have completed a series of focused field experiments targeting resolution of flow hydrodynamics over a range of reef environments in varying wave and current conditions, with concurrent high resolution roughness mapping. Additional observations have also been carried out that leverages funding from the Army Corps of Engineers in collaboration with Mark Merrifield (UH Oceanography).

To date, we have carried out complete field observations at six different reef locations, in three distinct geographic regions (Oahu, Guam, Palau). Observations have focused primarily on forereef regions at each site, where roughness height is small relative to the depth and wave breaking can typically be

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neglected. Results from these simpler domains can then provide a foundation for examining more complex roughness environments. The field experimental plan for each site features one or two bottom-mounted instrument packages, each with an upward looking 1200 KHz ADCP with 3 ADVs deployed on a nearby vertical spar, alongshore from each other and separated by roughly 200m, at a depth of between 10 and 20 m. These packages target resolution of velocity profiles and Reynolds stresses. Instruments were deployed at each site for a period of about two weeks to resolve a range of wave and current conditions.

In order to quantify the relationship between the hydrodynamic response and the physical characteristics of the reef, we have carried out high-resolution roughness surveys at each site using a REMUS AUV equipped with a narrow beam acoustic altimeter and sidescan sonar. Surveys consist of dense ‘mow’ patterns in both along- and cross-shore directions with the vehicle operating at altitudes of 3-5 meters above the bed at depths ranging from 5 to 30 m. For the Kilo Nalu site, for example, this covers an area of roughly 0.5 km<sup>2</sup>.

We have also carried out AUV ‘hydrodynamics’ surveys at each site targeting the spatial evolution of current BL structure in response to the variable reef roughness. Our earlier work has shown that the REMUS ADCP can be effective in resolving steady BL structure with spatial averaging of 50-100m (Jaramillo & Pawlak, 2010). Analysis of along-track velocities has shown evidence of weak velocity bias in the direction of platform motion consistent with other observations from vessel and AUV-mounted ADCPs (Fong & Monismith, 2004; Fong & Jones, 2006). In Jaramillo & Pawlak (2010), we further characterize the variability in this bias with changes in sampling parameters. Cross-track velocities have not shown any evidence of bias, however. Surveys thus focus on repeated cross-shore transects over the course of a tidal cycle to enable resolution of along-shore velocity profiles.

One postdoctoral researcher, Sergio Jaramillo, has received support from this ONR project. The project has also provided partial support for research technicians, Kimball Millikan and Chris Colgrove, who have participated in field operations and experiment design.

## **WORK COMPLETED**

The project efforts have focused on quantitative characterization of substrates and corresponding roughness in coral reef environments along with investigation of AUV capabilities for detailed hydrodynamic measurements. The UH REMUS AUV was outfitted with a narrow-beam (2.5° beam width) altimeter with a sampling frequency of up to 18Hz, which enables resolution of small-scale bed roughness over hydrodynamically relevant scales. We have completed analysis of substrate characterization (Jaramillo & Pawlak, 2011) and are continuing analysis of new roughness data from multiple project sites. A follow-up project (N00014-11-1-0440) funded new observations with analysis ongoing.

The first series of AUV surveys were carried out at the Kilo Nalu Observatory on the south shore of Oahu (Pawlak et al, 2009) in 2010. A full set of AUV surveys, with fixed-point turbulence measurements at 10m depth and cross-shore wave observations, was obtained in Dec. 2010 on the north shore of Oahu. The observational period featured wave heights over 4m. Field observations were carried out at multiple sites around the island system of Palau in March 2011 and again in March 2012, in collaboration with researchers at UCSD SIO and University of Delaware (Terrill, Moline). The 2011 AUV and fixed-point observations focused on two sites: a current dominated lagoon patch reef and a wave-dominated reef pass. Field work in 2012 focused on a forereef environment with

variable wave and tidal forcing. In addition, a number of joint AUV surveys were carried out over a range of environments including river mouths, reef flat and fore-reef sites. Further AUV surveys and bottom turbulence measurements were carried out along the eastern Guam coast in August 2011.

## RESULTS

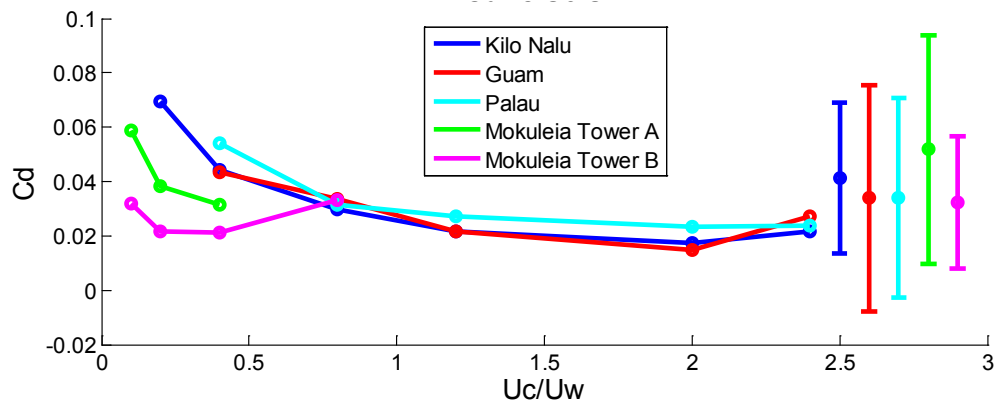
The AUV resolves bed features at a horizontal resolution of  $\sim 5\text{cm}$  for sidescan backscatter data, and  $\sim 10\text{cm}$  for altimeter data. Compared to boat-derived roughness measurements (Nunes & Pawlak 2008), the use of an AUV for this task improves the quality and resolution of the data obtained by increasing platform stability and by maintaining a near-constant acoustic footprint for the altimeter-based roughness measurements. Methodologies for substrate characterization along with roughness characteristics for the Kilo Nalu reef are detailed in Jaramillo & Pawlak (2011). Given general substrate classifications from sidescan data, physical bed roughness is assigned for rough reef, bare reef and sand. For the Kilo Nalu surveys, rms roughness over wavelengths between 0.2 and 0.6 ranged from 3.3 cm for bare reef to 7.3 cm for rough reef areas.

Analysis of roughness data from other survey locations has continued. Estimates of average drag and roughness characteristics are given in Table 1 for 5 sites analyzed to date. Relevant parameters during the observational window are also listed. Figure 1 shows variations in drag coefficient for each site, as a function of the current/wave velocity ratio. Drag data is obtained from log fits to ADCP velocity profiles, with values validated from estimates using dissipation data from nearby ADVs.. Existing theory (Grant and Madsen, 1979; Christofferssen and Jonsson, 1985) would suggest an increase in drag at low  $U_c/U_w$  with  $C_D$  approaching constant values at high  $U_c/U_w$  with the magnitude determined by the bed roughness. Although the observations do suggest an increase at low  $U_c/U_w$ , interestingly, for strong currents/weak waves, values for  $C_D$  all show consistent values, despite significant variations in roughness RMS (table 1). There is considerable scatter in the drag data, however, so further analysis of turbulent characteristics is underway.

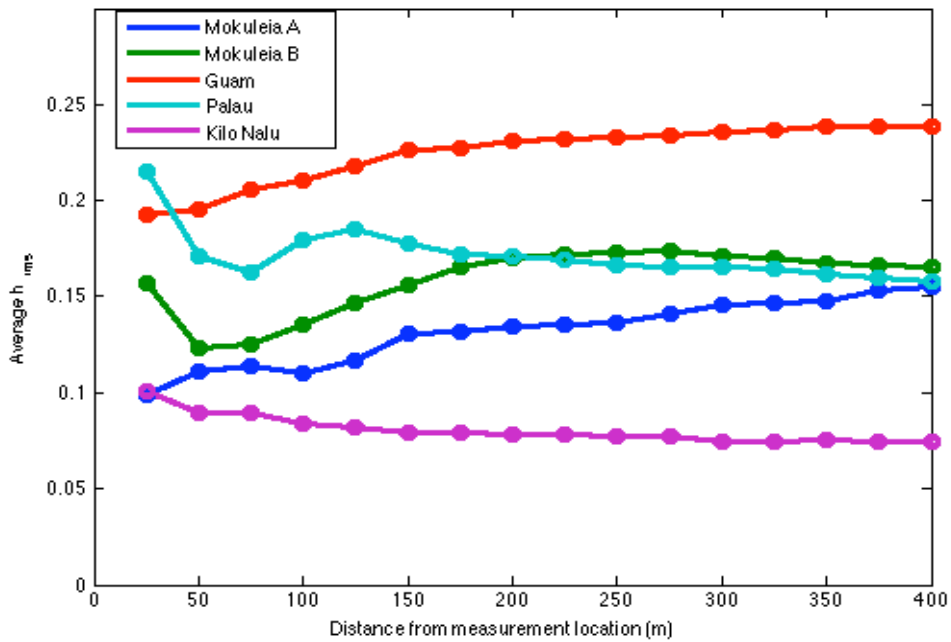
A key focus for continuing efforts is to establish hydrodynamically relevant length scales for flow over coral reefs. The distance over which roughness affects hydrodynamic observations, for example, is not well established. Figure 2 illustrates the spatial inhomogeneity in reef roughness. The figure shows variation in average RMS roughness as the spatial averaging scale increases. In addition, roughness estimates also depend on direction (not shown). These spatial variations in roughness estimates likely play a role in the variations in  $C_D$  at low  $U_c/U_w$  and the uniformity at high  $U_c/U_w$ , but further analysis is required to understand these observations.

Table 1 - Average drag and roughness characteristics for tropical reef locations along with average current/wave velocity ratios and wave orbital amplitudes during observations. Roughness RMS is calculated over 12 m segments.

Site	$C_D$	RMS Roughness (m)	$U_c/U_w$	A (m)
Kilo Nalu	0.041	0.08	0.54	0.40
Mokuleia A	0.052	0.13	0.18	0.86
Mokuleia B	0.032	0.16	0.21	0.91
Guam	0.034	0.22	1.91	0.16
Palau	0.034	0.17	2.05	0.25



*Figure 1 - Aerial image of North Shore Oahu study site (Mokuleia). Roughness data from one survey is overlaid with LIDAR bathymetry.*



*Figure 2 – Variation in average reef roughness RMS vs spatial averaging distance from location of fixed instrumentation.*

Observations at each site have also included a series of AUV surveys targeting the spatial structure of the flow field and water properties at each site. Observations of currents have been complicated by bias in DVL data in the direction of vehicle motion, as mentioned above. Each survey, therefore, includes legs in opposite directions, centered on fixed-point current measurements to assess DVL performance. Profiles of bias velocities can then be determined and analyzed. Observations reveal a bias with a near-field decaying profile and a far-field profile increasing with distance beyond some threshold range. Analysis indicates that the far-field bias has some dependence on acoustic backscatter levels, while the near-field bias is uniformly present.

## **IMPACT/APPLICATIONS**

Coral reefs are a dominant feature of coastal environments at low latitudes. Effective littoral operations in reef environments require accurate prediction and modeling of wave and current dynamics over complex boundaries as well as characterization of acoustic and optical processes. Turbulent processes at the seabed are at the foundation of littoral hydrodynamics with the bed shear stress as a key parameter affecting dissipative and dispersive mechanisms.

In addition to direct effects on nearshore hydrodynamics, turbulence over rough beds influences optical and acoustic properties. Bed roughness also directly affects acoustic propagation in the coastal zone. The observations described here will enable more general characterization of bed morphologies in reef zones and will establish foundation for remote sensing of bed characteristics from aerial and satellite imagery. Beyond applications in coral reefs, the research is extending understanding of hydrodynamics of flow over complex boundaries in general.

The work described above has enabled new research applications focusing on benthic roughness mapping and classification, which have implications for nearshore wave and current modeling. Combined with direct measurements of roughness from a narrow-beam altimeter recently added to the UH AUV, sidescan imagery can provide valuable 2D context, enabling substrate identification and classification in complex reef environments. These observations can potentially be correlated with remote sensing methods to provide benthic classification with more extensive spatial coverage.

The detailed analysis of AUV DVL performance, underway as part of the ongoing work, is critical for development of AUV-based spatial hydrodynamic sampling. AUV spatial surveys can, in turn, provide a key tool for assessment and characterization of nearshore processes on complex coastlines.

## **RELATED PROJECTS**

The work discussed here has been directly motivated by results from earlier ONR funded projects including a Young Investigator grant that focused on wave boundary layer dynamics and led to the establishment of the Kilo Nalu Observatory. The REMUS AUV was acquired via an ONR DURIP. S. Jaramillo was also supported as a postdoc via an ONR grant to develop AUV capabilities at Kilo Nalu. Ongoing NSF-funded projects at Kilo Nalu are focused on wave and current boundary layer turbulence in the context of benthic geochemical exchange and stratified turbulence.

A USACE funded project (PI: Merrifield) targeting wave transformation and coastal flooding for island shorelines includes AUV-based roughness surveys at Guam, is enabling extension of the work described here providing an additional data set for analysis. We are also coordinating with an NSF funded project (PI: Merrifield) targeting wave transformation and coastal flooding for island

shorelines. Project PIs are collaborating to carry out further observations that will enable extension of the work described here and providing an additional data set for analysis.

The work described here has also been carried out in parallel to a separate, complementary ONR funded project that is examining variability in optical and acoustic water properties for tropical reef environments and their relation with hydrodynamic forcing. Some of the AUV surveys and hydrodynamics observations described above provide data relevant to both projects and some analysis efforts overlap. Further observations in support of this project will also yield useful data sets for the reef roughness work.

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## PUBLICATIONS

The following publications have been produced under support of this project.

- Jaramillo, S. and G. Pawlak, AUV-based bed-roughness mapping over a tropical reef, *Coral Reefs*, submitted, September 2010.
- Jaramillo S. and G. Pawlak, AUV-based observations of rough bed hydrodynamics, *Proceedings IEEE AUV2010 Conference*, Monterey, September 2010